

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188	
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1. AGENCY USE ONLY (Leave Blank)		2. REPORT DATE 2-24-04		3. REPORT TYPE AND DATES COVERED Final Progress 9-25-00 to 11-30-03
4. TITLE AND SUBTITLE Engineered Photonic Materials for Nanoscale Optical Logic Devices			5. FUNDING NUMBERS DAAD19-00-1-0556	
6. AUTHOR(S) Steve Blair				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Utah 1471 Federal Way Salt Lake City, UT 84102-1870			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSORING / MONITORING AGENCY REPORT NUMBER 41374.6-PH-YIP	
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.				
12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12 b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Two major activities of this grant were to develop a generalized approach to the enhancement of nonlinear optical effects based upon slow-light propagation in artificial resonators and the study of nonlinear self-focusing in periodic arrays of photonic microcavities, thereby providing a mechanism for the formation of very narrow (i.e. wavelength scale) spatial solitons at very low powers.				
14. SUBJECT TERMS photonic bandgap, nonlinear optics, optical solitons, microresonators			15. NUMBER OF PAGES 5	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

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Manuscripts Submitted

Yan Chen, Geeta Pasrija, Behrouz Farhang-Boroujeny, and Steve Blair, "Engineering the nonlinear phase shift using artificial resonances," submitted to Journal of the Optical Society of America B, (2004)

Cumulative Manuscripts Published

Yan Chen, Geeta Pasrija, Behrouz Farhang-Boroujeny, and Steve Blair, "Engineering the nonlinear phase shift," Optics Letters **28**, 1945 (2003)

Yan Chen and Steve Blair, "Nonlinear phase shift of cascaded microring resonators," Journal of the Optical Society of America B **20**, 2125 (2003)

Steve Blair, "Self-focusing of narrow 1-D beams in photonic microcavity arrays," Journal of the Optical Society of America B **20**, 1520 (2003)

Steve Blair, John Heebner, and Robert W. Boyd, "Beyond the absorption limited nonlinear phase shift with ring resonators," Optics Letters, **27**, 357 (2002).

S. Blair, "Nonlinear sensitivity enhancement using 1-D photonic bandgap microcavity arrays," Optics Letters **27**, 678 (2002).

S. Blair and K. Wagner, "Gated Logic with Optical Solitons," *Collision-Based Computing*, edited by Andrew Adamatzky, Springer-Verlag (2002)

S. Blair "Spatial solitary waves and nonlinear k-space," A. D. Boardman and A. P Sukhorukov (eds.) *Soliton Driven Photonics*, p. 245-249 (2001)

S. Blair "Anomalous loss scaling in periodically absorbing media," JOSA B **18**, 1943 (2001)

Cumulative Conference Presentations

Steve Blair, "Self-focusing in photonic crystal defect arrays," Optical Society of America Annual Meeting, Paper TuS6, Tucson, Oct. 2003.

Steve Blair, Yan Chen, Geeta Pasrija, and Behrouz Farhang-Boroujeny, "Digital filter design approach to optimizing nonlinear optical response in multiple resonator structures," Optical Society of America Annual Meeting, Paper TuS6, Tucson, Oct. 2003.

S. Blair, Y. Liu, B. Yellempalle, and K. Wagner, "Nonlinear phase shift of photonic microcavity arrays," CLEO, May 2002.

Y. Chen and S. Blair, "Engineering the nonlinear phase shift," Nonlinear Optics, July 2002.

Steve Blair, Yan Chen, Geeta Pasrija, and Behrouz Farhang-Boroujeny, "Engineering the nonlinear phase shift with artificial resonances," Physics of Quantum Electronics, Jan. 2003, Snowbird, UT.

Yan Chen, Benjamin Yang, Geeta Pasrija, and Steve Blair, "Engineering the nonlinear phase shift," Nonlinear Optical Guided Waves, Aug. 2002, Stresa, Italy.

S. Blair "Restoring logic with optical solitons," NATO ASI on Soliton Driven Photonics, Swinoujscie, Poland, Sept. 2000.

Scientific Personnel

Steve Blair, Assistant Professor.

Yan Chen, Graduate Research Assistant. Ms. Chen has been developing the generalized approach to enhancing nonlinear optical phenomena. She has also performed nonlinear device fabrication and characterization. She will receive her PhD during the Summer of 2004.

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Scientific Progress and Accomplishments

The detailed study of the nonlinear response of resonant optical structures began after a conversation with Dr. Ciftan in April 2001, at which time he suggested that I investigate resonant structures for low-power soliton formation. The first structure we studied is shown in Figure 1 along with the corresponding linear phase shift and intensity transmittance. This structure consists of a periodic array of microcavities (or defects) in a one-dimensional photonic crystal. The layer sequence for these structures can be written:

$$(LH)^3 \left[(H)^7 (LH)^6 \right]^{N-1} (H)^7 (LH)^2 L \quad (1)$$

where L represents a quarter wave low index layer, H represents a quarter wave high index layer, and N is the number of microcavities composed of eight quarter wave layers

The defect array opens up photonic density of states within the bandgap, resulting in transmission resonances. It is these transmission resonances that are studied for their large nonlinear response. There are many parameters for optimization, such as refractive index contrast between L and H, number of LH periods between defects, number of defects, and defect size. The nonlinear response of resonant structures results from intensity-induced detuning of the resonance. Therefore, in the weak nonlinearity limit, the nonlinear properties can be deduced from the linear properties of transmission and phase. This is a powerful concept that is exploited throughout our research to optimize the nonlinear response.

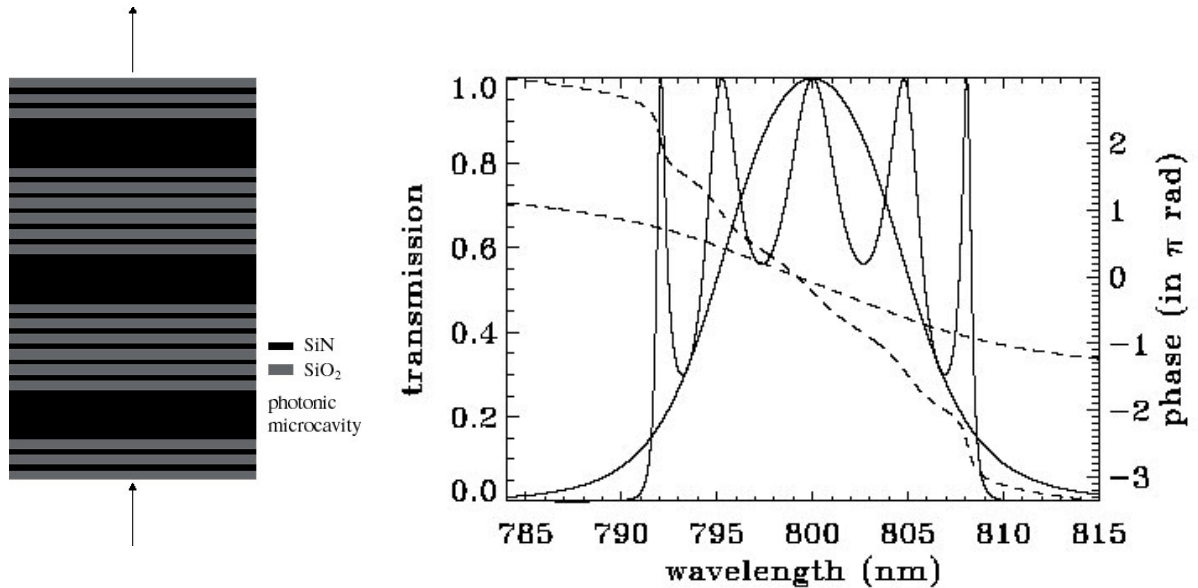


Fig. 1. Multilayer thin film geometry of the photonic microcavity array (left). The structure consists of alternating low (SiO₂) and high (SiN) index layers, that are quarter wave at 800 nm. The high index cavities consist of 8 quarter wave SiN layers. Phase (dashed linestyle) and intensity transmittance (solid) across the transmission resonance of the one-dimensional photonic microcavity array of three (thin lines) and seven (thick lines) microcavities. The bandgap extends from about 710nm to 910nm.

Figure 2 shows a calculation of the nonlinear phase shift of a 15 ps pulse (centered on 800 nm) upon propagation through these structures as a function of incident intensity and N. As N increases, the phase shift increases. Also plotted in Figure 2 is the nonlinear phase shift for bulk materials of the same thicknesses as the corresponding photonic microcavity array structures. For the structure with an array of 31 microcavities, the enhancement in the nonlinear sensitivity is about 13 at low intensities, but reduces to 8 at higher intensities due to saturation. A figure of merit is plotted in Figure 2 which is defined by $FOM = (\Delta\phi/\pi)(eT)$, where T is the intensity transmittance. More detailed studies have shown that the sensitivity increases with increasing microcavity size, and increasing number of reflecting layers. Enhancements by nearly a factor of 100 have been predicted with only slight modifications to the present structure, with figures of merit exceeding unity

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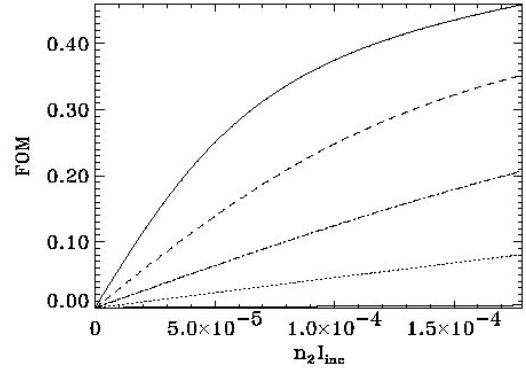


Fig. 2. Nonlinear phase change (left) and figure of merit (right) for a photonic microcavity array for $N=15$ (dashed, heavy), $N=7$ (dot-dashed, heavy), and $N=3$ (dotted, heavy, which partially overlaps the solid line for the bulk phase shift). Phase shifts for bulk materials of the same thicknesses as the corresponding microcavity arrays are shown in the thin linestyle.

An $N=3$ microcavity structure has been fabricated using sputter deposition of SiO_2 and SiN layers followed by a high temperature annealing step, with a target intragap resonance at 800 nm. Figure 3 shows the transmission spectrum of one sample. We are working on a better annealing process in order to increase the transmission closer to 100%. Z-scan measurements were taken using a Ti:Sapphire mode-locked oscillator, which indicate a strong nonlinear phase shift from the structure, as shown in Figure 3. A z-scan of the substrate material alone had a peak to valley excursion of nearly 100 times less, indicating that the phase shift comes from the 10 μm multilayer structure. In addition, a z-scan of the structure was taken using cw light of the same average power as the mode-locked measurement. This measurement also had a very small excursion, indicating that the nonlinear phase shift is not dominated by thermal effects.

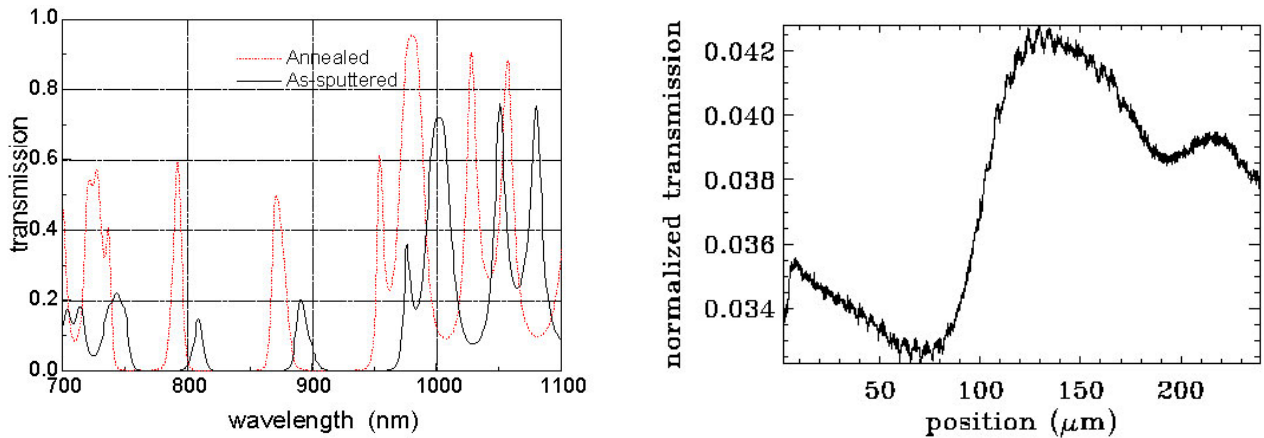


Fig. 3. Transmission spectrum (left) and Z-scan measurement (right) at 800 nm for the $N=3$ microcavity array structure of Figure 1.

We have extended these studies to a generalized design approach for nonlinear processes, which involves treating a collection of artificial resonators as a discrete time filter. With this perspective, all of the tools of digital signal processing can be brought to bear on the problem. Fig. 4 illustrates the notion of producing a nonlinear phase shift response through the nonlinearly-induced detuning of a periodic (i.e. digital) bandpass transmission filter, where the slope of the phase determines the group delay. The digital filter is initially synthesized in terms of the poles and zeros of the transfer function; this design is then mapped into an optical architecture. There are two means to increase the group delay (and hence, the nonlinear response)

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within the passband: 1) decrease the passband width and/or 2) increase the in-band phase change, which can be accomplished by increasing the order of the filter.

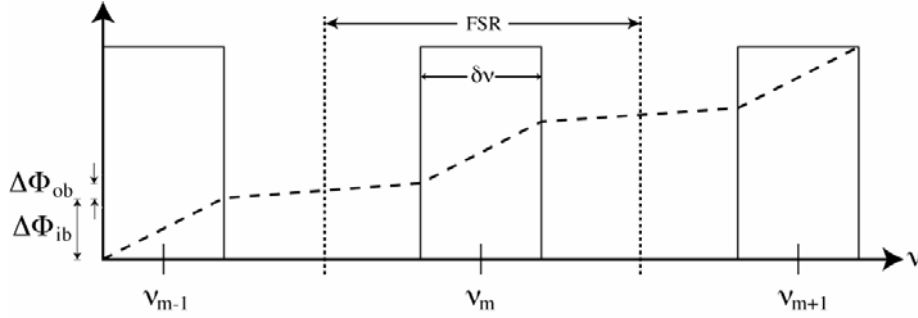


Fig. 4. Magnitude and phase response of a digital bandpass filter that produces an ideal nonlinear phase shift.

Fig. 5 shows the nonlinear response obtained by mapping the transfer function of Fig. 4 onto an optical ARMA architecture consisting of Mach-Zehnder ring resonator lattice filter stages. The nonlinear response is greater than that of an unstructured material of equal group delay, but there is a point at which bistable behavior occurs. By adding more stages, a greater nonlinear response can be obtained without sacrificing linear bandwidth.

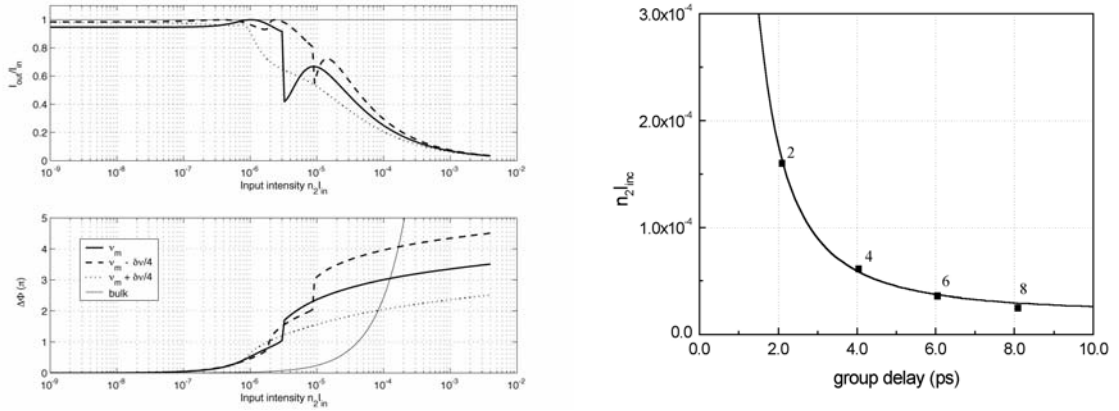


Fig. 5. Nonlinear phase shift response of four-stage ARMA filter (left). The nonlinear response is enhanced by 17 times over the bulk material of equal group delay. Scaling of nonlinear response $n_2 I$ with group delay (right) for a constant passband width of 500-GHz, where group delay is increased by increasing the number of stages. Designs with 2, 4, 6, and 8 stages are shown.

The self-focusing of optical beams in nonlinear media is a fundamental nonlinear optical process that has many practical ramifications. In some circumstances, self-focusing is an undesirable process, while in other circumstances such as soliton formation, it is desirable to enhance the self-focusing process. Here, self-focusing is studied in coupled arrays of photonic microcavities that take the form of periodic defects in a photonic bandgap structure. The threshold intensity for self-focusing can be reduced significantly over bulk even when the symmetry of the resonant structure demands that the rate of linear beam spreading is increased.

For comparison purposes, a narrow scalar soliton in bulk media is described by the nonlinear Helmholtz equation

$$\frac{\partial^2 A}{\partial z^2} + \frac{\partial^2 A}{\partial x^2} + k_0^2 \left(1 + 2 \frac{n_2}{n_0} |A|^2 \right) A = 0$$

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which has the solution valid for any width

$$A = A_0 \operatorname{sech}\left(\frac{x}{w_0}\right) e^{i\beta z} \quad A_0 = \frac{1}{k_0 w_0} \sqrt{\frac{n_0}{n_2}} \quad \beta = k_0 \sqrt{1 + \frac{n_2 A_0^2}{n_0}}$$

The fractional nonlinear refractive index change required is given by

$$\Delta n = \frac{n_2 I}{n} = \frac{\lambda^2}{4\pi^2 w_0^2} = \frac{1}{4\pi^2 \chi^2}$$

Therefore, as the soliton width approaches the wavelength, the required index change approaches 0.025, which is far larger than can be sustained by most transparent nonlinear media. Defining the confocal distance $z_0 = k_0 w_0^2$, the total integrated nonlinear phase change required for a soliton to propagate a distance dz_0 is given by

$$\Delta\phi = \frac{d}{\kappa^2} \left[\sqrt{1 + \kappa^2} - 1 \right] \quad \text{where } \kappa = \frac{1}{2\pi\chi}$$

The total phase change is nearly constant with width at $\Delta\phi \approx 0.16\pi d$, and reduces slightly as the width becomes smaller than the wavelength. The total phase shift illustrates how efficient solitons are as nonlinear phenomena; they are clearly observable with much less than a π phase shift.

These properties are useful in the comparison between bulk solitons and solitons of photonic microcavity arrays. For example, the fractional index change required in bulk for a wavelength scale soliton is too great to be practical, but, because the nonlinear phase change is amplified due to detuning in the microcavity array, large effective index change results from small physical index change. In addition, even physically small microcavity array structures (i.e. $10\mu\text{m}$ in length) can produce the total phase changes required for extended soliton propagation. Therefore, photonic microcavity arrays are ideal for the propagation and interaction of narrow, wavelength-scale, spatial solitons.

Fig. 6 shows one geometry of interest and the corresponding linear phase and intensity transmittance for structures with three 1-D, planar microcavities. L represents a quarter-wave low index (1.46) layer for 800 nm wavelength, H represents a quarter-wave high index (2.1) layer, M is the number of LH layer pairs in the Bragg reflectors surrounding each microcavity, and N is the number of microcavities composed of eight quarter-wave high index layers. Fig. 7 shows the results of self-focusing, where the self-focusing threshold is reduced by up to a factor of 8 ($M=4$) compared to bulk, even though linear diffraction is enhanced by a factor of 5. The output beam profiles show the formation of sidelobes near the self-focusing threshold. Similar results are obtained for self-focusing in a 2-D square defect lattice in a 2-D photonic crystal, but where linear diffraction can be significantly reduced.

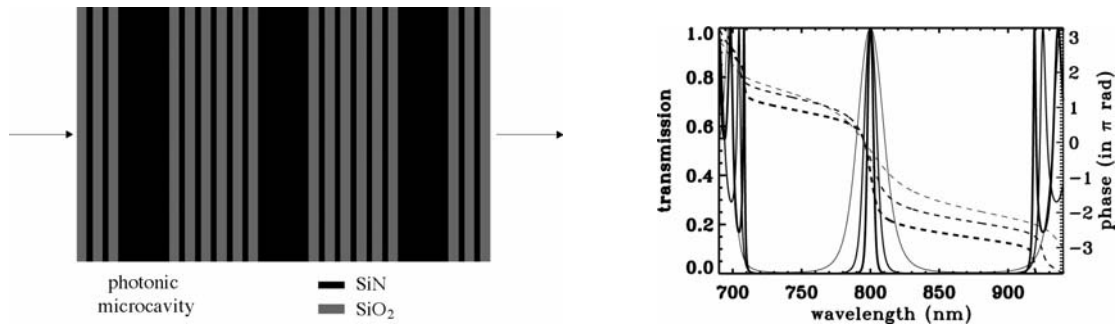


Fig. 6. Planar photonic microcavity array (left) with layer sequence $(\text{LH})^M[(\text{H})^7(\text{LH})^{2M}]^{N-1}(\text{H})^7(\text{LH})^{M-1}\text{L}$ with $M=N=3$. Intensity transmittance (right, solid linestyle) and phase (dashed) of the transmission resonances with $N=3$, and $M=2$ (thin), $M=3$ (medium), and $M=4$ (thick). As shown, the bandgap extends from 710nm to 920nm.

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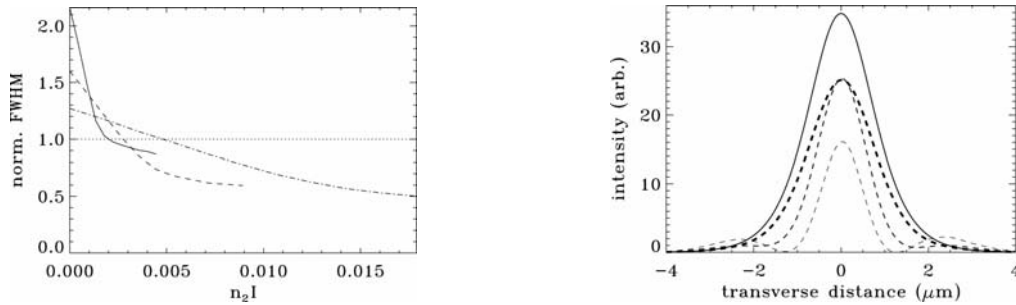


Fig. 7. Output beam FWHM (left) normalized to the 1.76 μm input FWHM as a function of normalized input peak intensity for microcavity arrays with $N=3$, and $M=2$ (dot-dashed linestyle), $M=3$ (dashed linestyle), and $M=4$ (solid linestyle). Transverse beam profiles (right) at the input (solid linestyle) and output (dashed linestyle) of the $M=3$ microcavity array structure. The heavy dashed line is for $n_2I = 2.7 \times 10^{-3}$, while for the medium and light line weights, $n_2I = 4.5 \times 10^{-3}$ and 8.9×10^{-3} respectively.

The enhanced rate of diffraction in a 1-D lattice might seem to be a drawback, even though it is accompanied by a reduction in soliton power. However, it turns out to be a great advantage. By increasing the curvature of the momentum surface that governs linear diffraction, the *interaction* between solitons is enhanced. Therefore, one soliton acting on another in a 1-D photonic microcavity lattice will be more effective than the same interaction in comparable bulk media. This is contrary to other soliton systems presently being studied such as waveguide arrays where the soliton power can be reduced, but there is a corresponding *decrease* in the strength of soliton interaction because diffraction forces are weakened. The 1-D microcavity array is the only system presently being studied that offers the simultaneous advantages of reduced power and enhanced interaction.

Also as part of this research, a femtosecond laser system was completed under funding from a second DURIP grant along with other matching funds. In addition to the Ti:sapphire oscillator funded by the first DURIP, we added a Spitfire regenerative amplifier and an optical parametric amplifier (OPA). The Spitfire is configured with dual ps/fs stretcher-compressor units so that we can rapidly switch between ps and fs operation with the same oscillator. The regen produces pulse energies exceeding 0.5 mJ. The OPA is setup for fs operation with tunability from 600 nm to 3000 nm and sub-50 fs pulse durations. Various nonlinear characterization experiments have been set up based upon this research.